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The High Chromospheres of the Late A Stars[1]

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ABSTRACT

We report the detection of N V 1239Å transition region emission in *HST*/GHRS spectra of the A7 V stars, α Aql and α Cep. Our observations provide the first direct evidence of $1-3\times10^5$ K material in the atmospheres of normal A-type stars. For both stars, and for the mid-A–type star τ^3 Eri, we also report the detection of chromospheric emission in the Si III 1206Å line. At a $B-V$ color of 0.16 and an effective temperature of $\sim$ 8200 K, τ^3 Eri becomes the hottest main sequence star known to have a chromosphere and thus an outer convection zone. We see no firm evidence that the Si III line surface fluxes of the A stars are any lower than those of moderately active, solar-type, G and K stars. This contrasts sharply with their coronal X-ray emission, which is >100 times weaker than that of the later-type stars. Given the strength of the N V emission observed here, it now appears unlikely that the X-ray faintness of the A stars is due to their forming very cool, $\leq$1 MK coronae. An alternative explanation in terms of mass loss in coronal winds remains a possibility, though we conclude from moderate resolution spectra of the Si III lines that such winds, if they exist, do not penetrate into the chromospheric Si III–forming layers of the star, since the profiles of these lines are *not* blueshifted, and may well be redshifted with respect to the star.

Subject headings: stars: activity — stars: chromospheres — stars: individual (α Aql, α Cep) — ultraviolet: spectra

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1. Introduction

In this paper we address a long-standing question in stellar structure as to the locus for the onset of subsurface convection zones in main sequence stars. Thirty years ago, the changeover from radiative to convective envelopes was presumed to occur in the close vicinity of spectral type F5 (e.g., Wilson 1966, Kraft 1967), an idea that was supported by optical observations of the time, which showed an absence of chromospheric Ca II emission reversals in the spectra of earlier stars and a steep falloff in the axial rotation rates of later stars (the direct result, it was reasoned, of magnetic braking and angular momentum loss due to the onset of coronal winds). In later years, however, improved stellar structure models as well as X-ray and ultraviolet (UV) observations from space have shown that coronae, chromospheres, and thus convection zones, must be present in stars that are located well above the F5 boundary line.

UV spectra from the *International Ultraviolet Explorer (IUE)* telescope, for example, trace chromospheric emission in Lα and in the 1335 Å lines of C II along the main sequence into the late-A stars, near $B-V = 0.20$ (Simon & Landsman 1991; Marilli et al. 1992; Landsman & Simon 1993), while a number of A stars have been detected in X rays by the *Einstein Observatory* or by *ROSAT* (Schmitt et al. 1985; Simon, Drake, & Kim 1995), including a handful of A0 stars with $B-V \approx 0.0$. The X-rays of the cooler A-type stars are believed to be coronal in origin. Those of the hotter stars are thought to come not from the A stars themselves, but from hidden late-type binary companions or neighboring stars that lie within the X-ray beam. Only rarely can this ambiguity be resolved (e.g, Schmitt & Kürster 1993). UV spectroscopy largely avoids this difficulty with the imagery, since the high temperature UV lines of a bright A star are expected to outshine those of virtually any low mass companion. On the other hand, the detection of chromospheric emission against the bright photosphere of an A star poses challenges of its own, demanding moderate-to-high spectral resolution, minimal scattered light, and exceptional signal-to-noise ratio. Such requirements were often beyond the capabilities of *IUE*, but can now be met routinely by instruments aboard *HST*, such as the Goddard High Resolution Spectrograph (GHRS).

In previous work with the GHRS (Simon, Landsman, & Gilliland 1994, hereafter SLG), we obtained high quality moderate resolution spectra of the C II 1335 Å lines for 8 mid- to late-A stars. Only in the case of the A7 V star, α Aql (Altair), did we find evidence for chromospheric emission. We chose the C II lines for this earlier study because they are among the brightest features in the UV spectra of G–M stars; moreover, the photosphere of an A star is much fainter at 1335 Å than it is at longer wavelengths, where the increasing brightness of the background can render even strong lines, such as C IV 1550 Å, completely invisible (Simon & Landsman 1991). The strongest A star chromospheric line accessible

to the GHRS is Lα. This line suffers the dual disadvantage of contamination by scattered light in the Earth's atmosphere and attenuation by interstellar H I along the line of sight to the star. Nonetheless, even at low resolution and low S/N, *IUE* spectra have yielded some detections among the late-A and early-F stars (Landsman & Simon 1993). Accordingly, with this *IUE* work in mind, we have initiated a program of GHRS Lα spectroscopy for a modest sample of bright A stars. Our goal was to establish more stringent constraints on the locus for the onset of main sequence convection zones. In this article, we report the initial results of our observations, which include the first detection of chromospheric emission in a mid-A type star, as well as the first detections of $\sim 10^5$ K N V 1239Å transition region emission in the spectra of two late A-type stars.

2. Observations

We acquired GHRS spectra of the 1200–1230 Å region at intermediate spectral resolution with the G140M grating and the small science aperture for seven mid- to late-A type stars. Two of the principal chromospheric lines located within this interval are Lα λ1215.67 and Si III 1206.51 Å. The latter is situated within the very dark, broad wings of the photospheric Lα line, which serves to enhance the contrast of the emission feature against the stellar background on which it lies. We summarize the results here for four stars (τ^3 Eri, Altair, α Cep, and α Hyi), but we postpone a discussion of the less well exposed spectra of three remaining stars (α Pic, ι UMa, and α Cir) to a later date. For two stars, Altair and α Cep, we obtained large aperture G140M spectra, centered on the Si IV $\lambda\lambda$1393.76, 1402.77 lines. These spectra cover the wavelength range from 1385 Å to 1415 Å. Photospheric absorption lines dominate the latter pair of spectra, and no transition region emission is evident in either one. We observed the same stars, i.e., Altair and α Cep, with the G140L grating and the large science aperture, obtaining coverage of the 1180–1440 Å region at low spectral resolution.

The above mentioned observations were carried out in the standard operational modes, as described by the GHRS *Instrument Handbook* (Soderblom et al. 1995). The relevant procedures include sub-stepping the spectrum by fractional diodes of the Digicon detector to improve the sampling, moving the spectrum by integral numbers of diodes to compensate for detector defects, and multi-diode rotations of the grating to facilitate the removal of fixed pattern noise. To calibrate the wavelength scales of our small aperture spectra, we obtained scans of an onboard Pt-Ne hollow-cathode lamp. The wavelength scales of the large aperture spectra were verified and corrected via the SPYBAL spectra that accompany each science observation (cf. Soderblom et al. 1995).

The data were analyzed within STSDAS/IRAF, with minor post-processing in IDL. In the way of an initial overview, Figure 1 shows our low resolution spectra of Altair and α Cep. In addition to Lα, several features, which cannot be seen even in the best images from *IUE* because of the high scattered light levels and low S/N ratio, are observed here for the very first time in A-star spectra. These include C III 1176 Å, Si III 1206 Å, and N V 1239 Å. The temperatures at which these lines form range from 3×10^4 K to 2×10^5 K. The presence of N V is particularly noteworthy, as it represents the highest excitation stage recorded to date in the UV for any normal A star. At longer wavelengths, there appears to be an emission feature near 1400 Å. In our G140M spectra, the same peak is located at 1394.34 Å, much too long a wavelength for it to be the transition region line of Si IV. According to an ATLAS9 model, this part of the photospheric spectrum is dominated by absorption lines of Fe II. We find, by numerically broadening the model flux distribution to $v \sin i = 240$ km s^{-1}, that there is a reasonable match to the overall shape of our G140L observation, including the observed "emission peak." We take this as an indication that the aforementioned peak is a window of reduced line blanketing rather than a strongly wavelength-shifted transition region emission line.

The Si III line profiles from three of our G140M small aperture observations are shown in Figure 2. The spectrum of τ^3 Eri is weak, but presents what we regard as marginal evidence for an emission line. A much deeper exposure is needed for confirmation. In the same spectrum, we see relatively intense emission in Lα, at a level of 2.9×10^{-13} erg cm^{-2} s^{-1}, and so there is no question but that τ^3 Eri has a chromosphere. At $B-V= 0.16$, τ^3 Eri becomes the earliest main sequence A star known to possess a chromosphere.

The broad, flat-topped shapes of the Si III spectra for Altair and α Cep, also shown in Figure 2, suggest considerable rotational broadening. However, in both cases the FWHM and FWZI imply $v \sin i \gtrsim 350$ km s^{-1}, which is substantially greater than the rotation rates of $\sim$240 km s^{-1} customarily cited for these stars. Other examples of excess broadening in GHRS spectra of later-type stars are discussed by Ayres et al. (1996). These authors offer several possible explanations for this effect, but find no entirely satisfactory answer. The wavelength centroids of the Si III lines of Altair and α Cep are centered on the radial velocities of the stars, or may be slightly offset by $+7 \pm 7$ km s^{-1}. Similar redshifts are observed for other late-type stars (Ayres et al. 1996). Our measurements of Altair and α Cep appear to rule out any possible wind outflow at chromospheric heights for both stars (see SLG), since if these lines were produced in a moderate-to-high velocity wind we would expect them to be appreciably blueshifted. Over the course of an *HST* orbit, neither star showed significant variability in Si III. Moreover, the G140M and G140L Si III line fluxes agree to within 4% for both stars. This sets limits on any longer-term (6–8 months) spectral variability, as well as on the extent of possible light losses and flux calibration uncertainties

in our small aperture spectra.

Table 1 summarizes the new UV line fluxes, along with revised C II fluxes for Altair and α Cep. The latter are based on the earlier study by SLG, except that we assume a brightness ratio of 8:1 in accordance with the relative strengths of the chromospheric lines listed in Table 1, instead of the 22:1 ratio adopted by SLG from consideration of low S/N spectra of Lα from *IUE*. Our revised C II fluxes for Altair and α Cep are in close agreement with, and only 18% higher and 18% lower, respectively, than those derived by Walter, Matthews, & Linsky (1995) by means of an entirely different approach.

3. Discussion

To gauge the intrinsic activity of the A stars, we use the Barnes-Evans (1976) relation to convert the apparent fluxes in Table 1, f_λ, to surface fluxes at the star, F_λ. The results are in Table 2, along with comparable numbers for X-ray emission. For comparison, we also tabulate surface fluxes for representative G and K stars. These values derive mainly from GHRS spectra (e.g., Ayres et al. 1997) or, in some cases, from compilations of *IUE* and *ROSAT* data that have appeared in the literature (e.g., Ayres et al. 1995).

In terms of their chromospheric or transition region fluxes, the A stars resemble moderately active late-type dwarfs or giants (e.g., ϵ Eri or β Cet), but they are (to no surprise) much less active than the rapidly-rotating Hertzsprung Gap giants (e.g., 31 Com) and the tidally locked RS CVn binaries (e.g., V711 Tau). In coronal X rays, the A stars are comparable to middle aged stars like the Sun and α^1 Cen. They are substantially less active than prototypical, rapidly rotating, young dwarf stars like χ^1 Ori. Nor are they as active as any of the late-type giants.

These trends are more clearly illustrated in the H–R bubble diagram shown in Figure 3. In this figure, we scale the diameter of the circle for each star to the common logarithm of the normalized flux value, $F_\lambda/\sigma T_{\rm eff}^4$. Turning to the top panel, we find no evidence in the Si III line for a decline in chromospheric activity along the main sequence, even among the middle A stars (that is, for effective temperatures as high as 8200 K) if one includes the uncertain measurement of τ^3 Eri. By contrast, the coronal X-ray fluxes in the lower panel of the figure show an enormous decline from one side of the diagram to the other, with the main sequence and more evolved early type stars to the left being considerably fainter than the late-type stars on the right. Attention was drawn to the lower coronal/chromospheric flux ratios among the early type stars by Simon & Drake (1989), who ascribed the effect to mass loss via coronal winds; a more recent discussion by Ayres et al. (1997) concludes that

the origin of these "X-ray deficits" may be related to the possible existence of very long coronal loops, but otherwise the trend remains unexplained. At intermediate, transition region temperatures, a similar trend may be appearing in the N V/Si III and N V/C II ratios, each being a factor of $2 - 3\times$ smaller among the A stars than among the G–K stars. However, given the lack of truly adequate numbers of high quality spectra of N V for stars of all MK classes, this possibility requires further study with the *HST*.

Continuing the tendency toward a broad dispersion in line strengths among the early F stars that was noted in our previous work (Simon & Landsman 1991; Landsman & Simon 1993), the surface fluxes of the A stars in Table 2 indicate that Altair is at least a factor of 2 more active than α Cep over the entire range of temperatures from chromospheric to coronal, despite the otherwise close similarities of these two stars (α Cep has the slightly lower surface gravity). Our spectra also largely put to rest the notion that the weak X-ray emission of these particular stars might be linked to a shift in their peak coronal heating below ~ 1 million K and to the formation of very cool coronae. The observed N V line strengths, and their ratios to fluxes of cooler chromospheric lines, make that appear extremely unlikely. However, only measurements of lines formed at 0.5–1 million K can answer this question for certain, and the needed observations await the launch of future space missions.

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Table 1. GHRS Emission Line Fluxes[a]

Star	HD	Sp. Ty.	$B-V$	f_{1176}	f_{1206}	f_{1239}[b]	f_{1335}
τ^3 Eri	18978	A4 IV	0.16	···	10	···	···
α Aql	187642	A7 V	0.22	160	175	21	540[c]
α Cep	203280	A7 V$^+$	0.22	18	23	2.2	68[c]
α Hyi	12311	F0 V	0.28	···	39	···	76[d]

[a]As observed at Earth. In units of 10^{-14} erg cm^{-2} s^{-1}.

[b]Includes only the stronger line of the doublet. The second line, at 1242.80 Å, is weak in the G140L spectrum of Altair and absent from the spectrum of α Cep. We believe this is due to absorption lines in the underlying spectrum of the photosphere.

[c]Assuming an α Aql/α Cep C II brightness ratio of 8:1. See text and SLG.

[d]From *IUE* spectrum, Simon & Landsman 1991.

Table 2. Emission Line Surface Fluxes[a]

Star	$B-V$	M_v	$T_{\rm eff}$	$L/L_\odot$	F_{1206}	F_{1239}	F_X
τ^3 Eri	0.16	2.63	8210	6.8	47	...	...
α Pic	0.21	1.85	7580	13.6	...	...	43
α Aql	0.22	2.30	7890	9.1	37	4.4	13
α Cep	0.22	1.60	7720	17.3	17	1.6	5.6
α Hyi	0.28	1.27	7190	24.0	34	...	42
β Cas	0.34	1.56	6870	18.5	59	7.7	47
α CMi	0.42	2.71	6270	6.6	28	5.4	60
χ^1 Ori	0.59	4.50	5800	1.3	...	3.9	1600
α Aur Ab	0.60	0.16	5580	72.5	120	23	200
β Hyi	0.62	3.81	5860	2.5	...	0.80	6.3
Quiet Sun	0.63	4.84	5771	1.0	9.5	0.64	20
31 Com	0.67	0.15	5570	73.0	150	27	1300
κ Cet	0.68	5.01	5510	0.9	...	6.2	950
ψ^3 Psc	0.69	~0.15	5520	73.0	110	18	180
α^1 Cen	0.71	4.37	5540	1.5	5.5	1.0	8.8
ϵ Eri	0.88	6.14	4940	0.4	19	4.9	610
α^2 Cen	0.88	5.71	5030	0.5	5.3	0.54	46
α Aur Aa	0.90	0.31	5190	73.2	15	6.4	150
V711 Tau B[b]	0.99	3.54	4860	4.1	280	88	38000
β Cet	1.01	0.95	4970	43.6	10	6.1	130
λ And	1.02	2.01	4750	17.3	46	22	1700

[a]In units of 10^3 erg cm^{-2} s^{-1}

[b]Entries are for the active K1 IV secondary star of this spectroscopic binary.

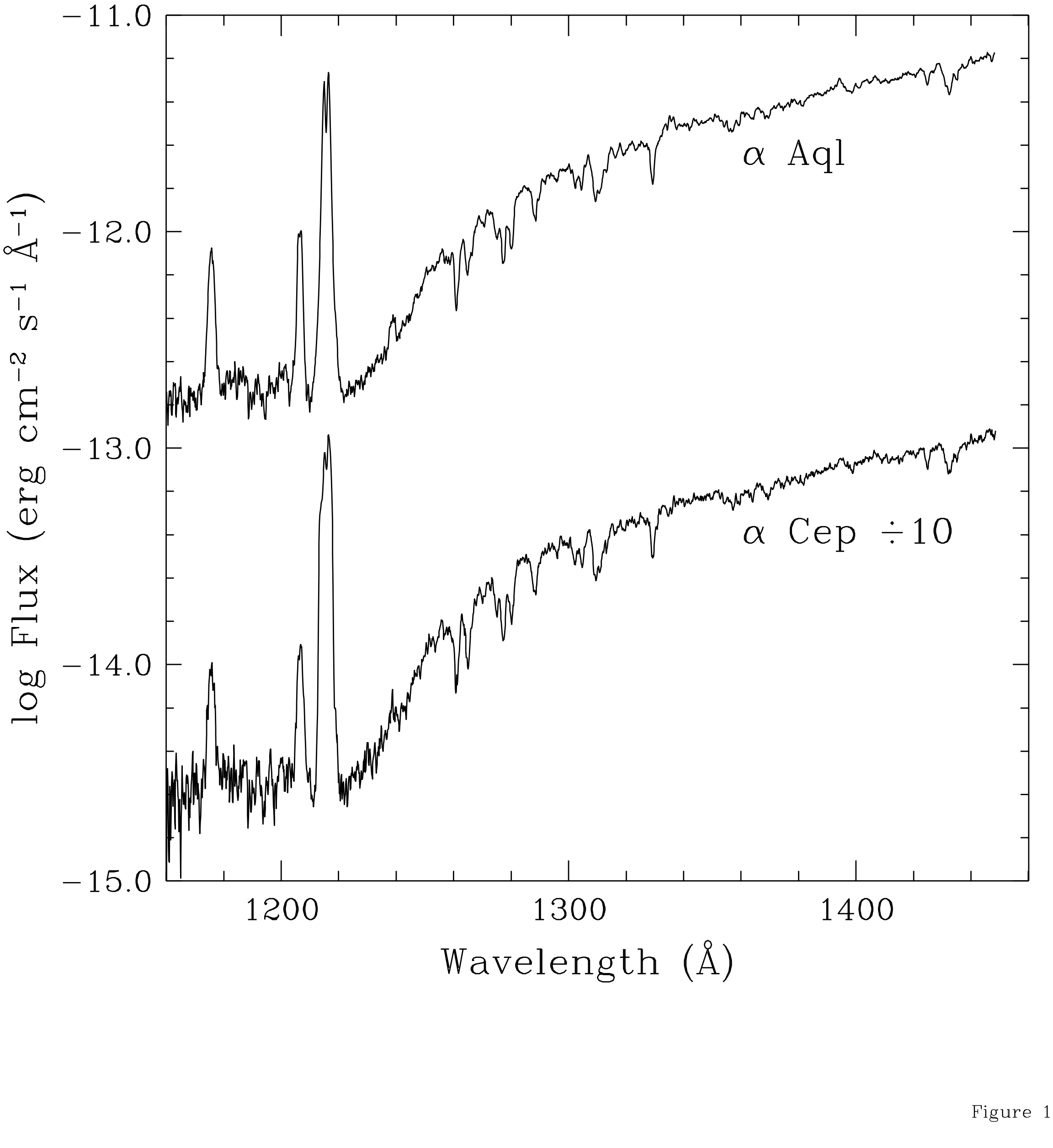

Fig. 1.— Low resolution GHRS G140L spectra of Altair and α Cep, showing stellar emission in C III, Si III, H I, and N V.

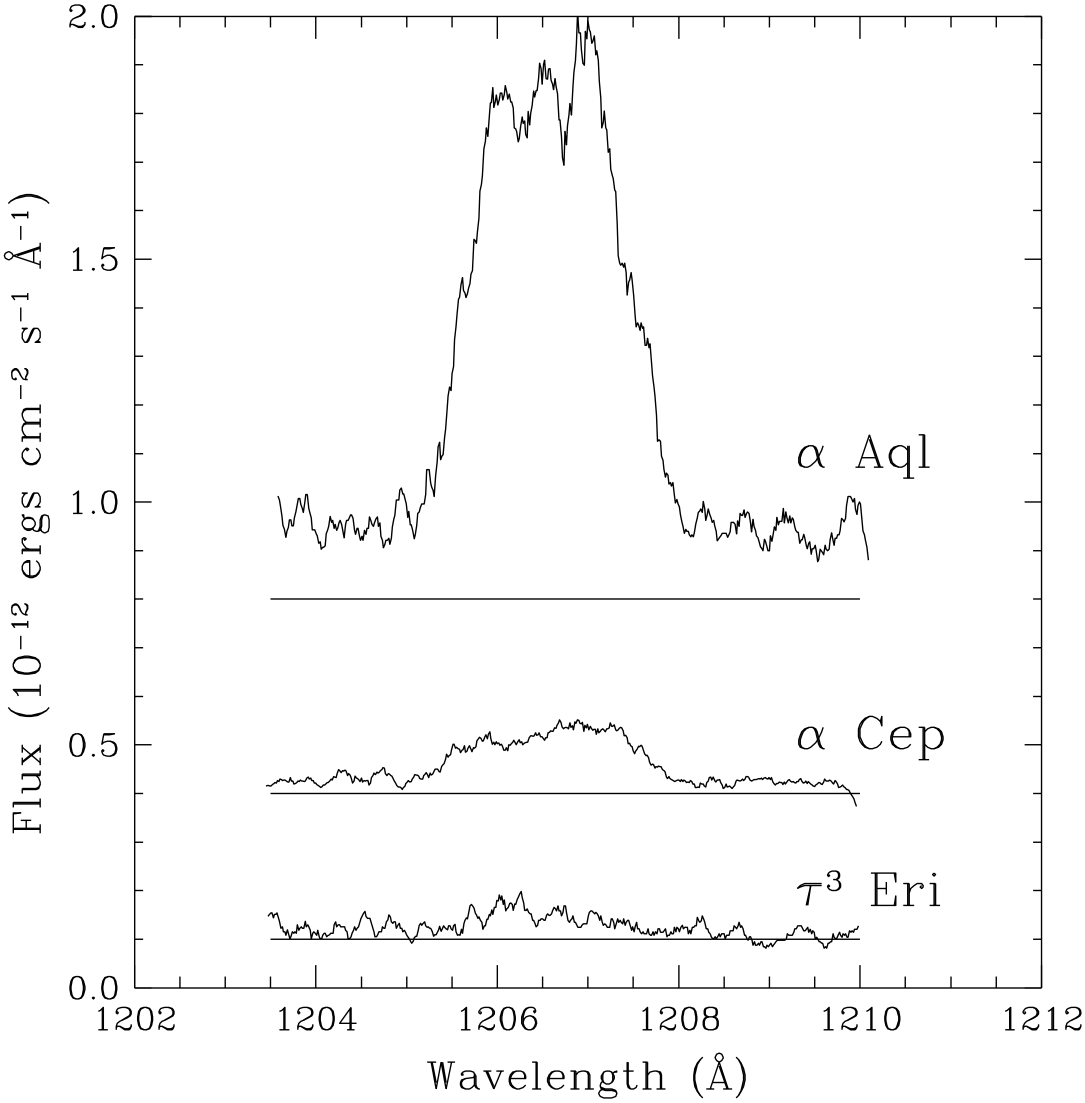

Figure 2

Fig. 2.— GHRS G140M small aperture spectra of Si III for three A stars. The data have been smoothed with a 3-diode running average. The individual profiles have been offset vertically, as indicated by the horizontal baselines.

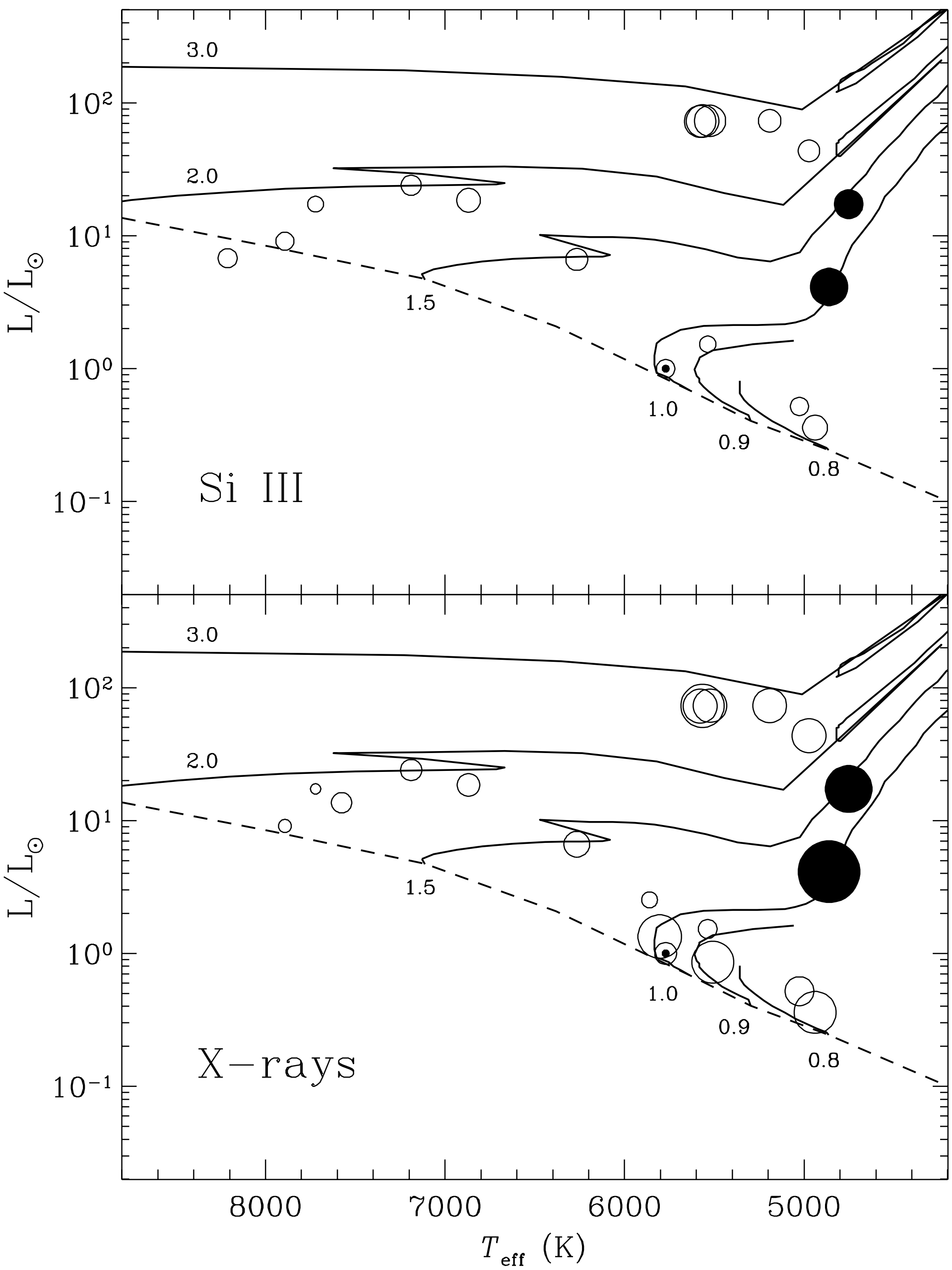

Figure 3

Fig. 3.— An H–R bubble diagram for the stars in Table 2. The dimensions of the circles are proportional to the log of the normalized flux, $\log(F_\lambda/\sigma T_{\rm eff}^4)$, for the Si III emission line (*top panel*) and for X-ray emission (*bottom panel*). The two large filled circles denote RS CVn binaries. The small dotted circle represents the Quiet Sun. The evolutionary tracks, with masses labeled in solar units, are from Schaller et al. 1992.